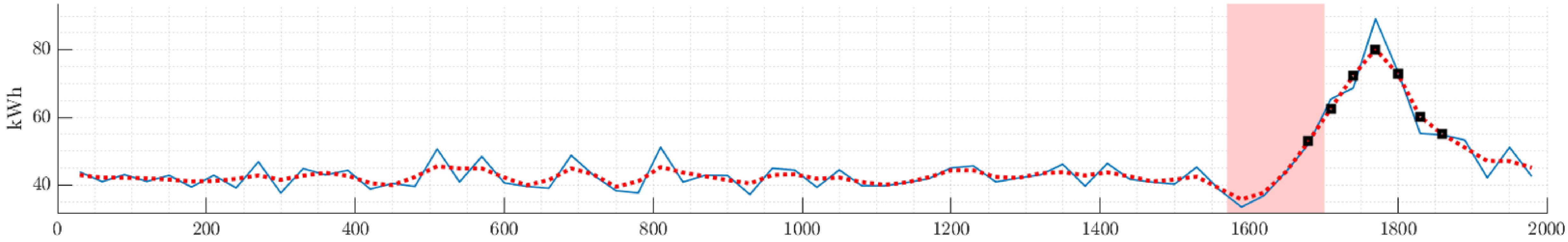

Reducing Power Peaks in Stochastic Railway Traffic Flow

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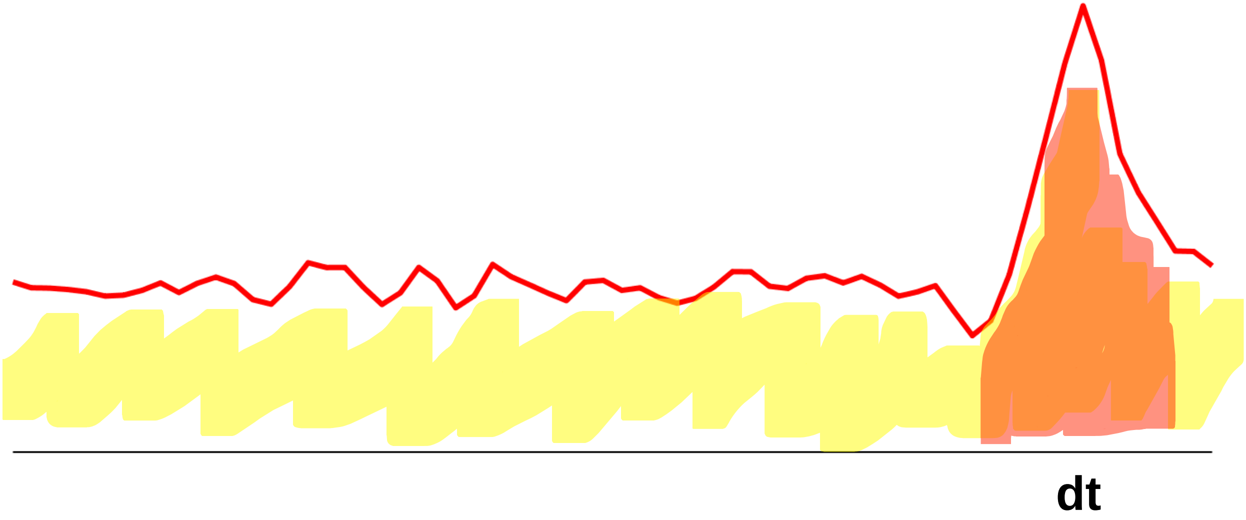
Joint work with: Francesco Corman (ETH Zurich)

hEART 2022

Background

- Transport accounts for a large share of energy consumption and global emissions (~16%[1])
- Despite railway is an efficient transport mode, much effort is devoted to reduce its consumption to cope with **increasing energy prices** and meet the **ambitious climate targets**
- Railway operators are concerned with both **energy use and peaks** in power needed: such peaks affect both grid stability and the energy bill



- Controlling energy use in a railway network is challenging as operations are subject to **uncertainties** affecting running and waiting times, train speed, line voltage, resistances, etc.

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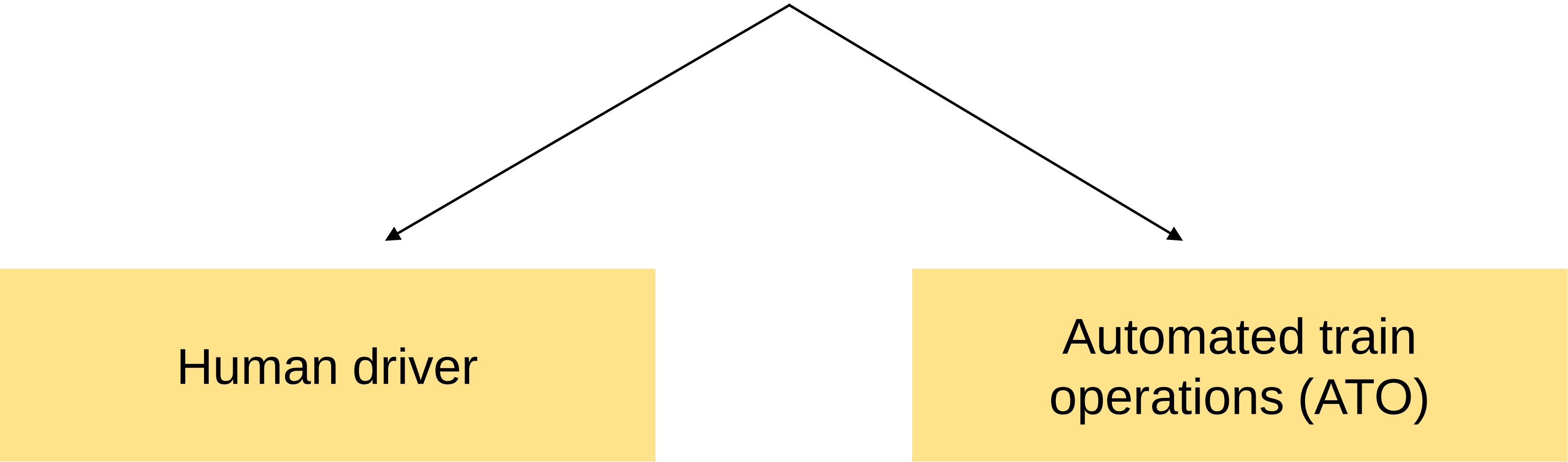
[1] https://ourworldindata.org/emissions-by-sector

Goals

1. Modeling railway traffic in a corridor by a string of consecutive trains subject to stochastic speed variations → we use **stochastic processes and simulation**
2. Analyzing the performance of such a dynamic system in terms of **regularity**, **energy use** and **power peaks**, depending on the assumptions on the processes

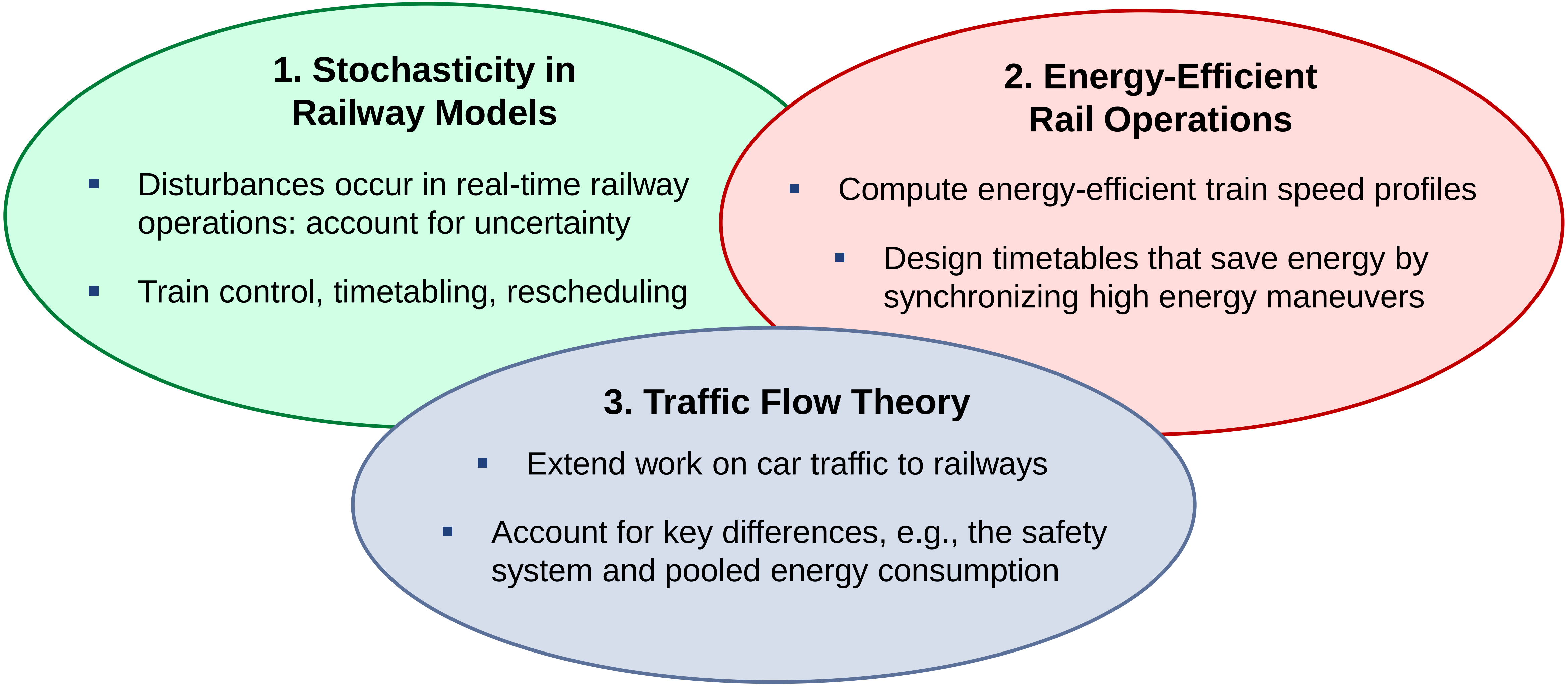


Human driver

Automated train operations (ATO)

Related literature

We draw a bridge between three different fields of research



1. Stochasticity in Railway Models

- Disturbances occur in real-time railway operations: account for uncertainty
- Train control, timetabling, rescheduling

2. Energy-Efficient Rail Operations

- Compute energy-efficient train speed profiles
- Design timetables that save energy by synchronizing high energy maneuvers

3. Traffic Flow Theory

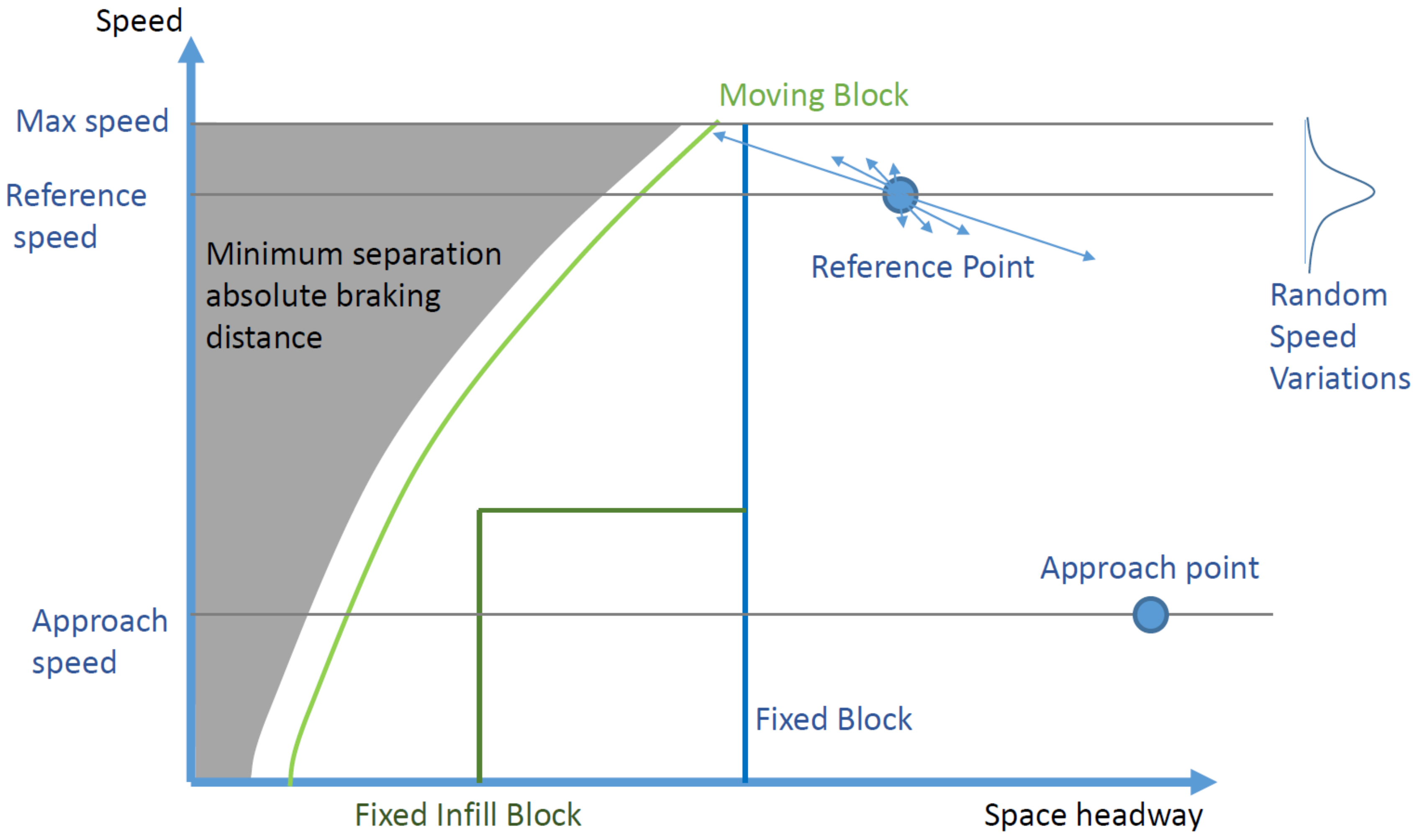
- Extend work on car traffic to railways
- Account for key differences, e.g., the safety system and pooled energy consumption

Previous work with 2 trains (Corman et al. 2021, TR Part C)

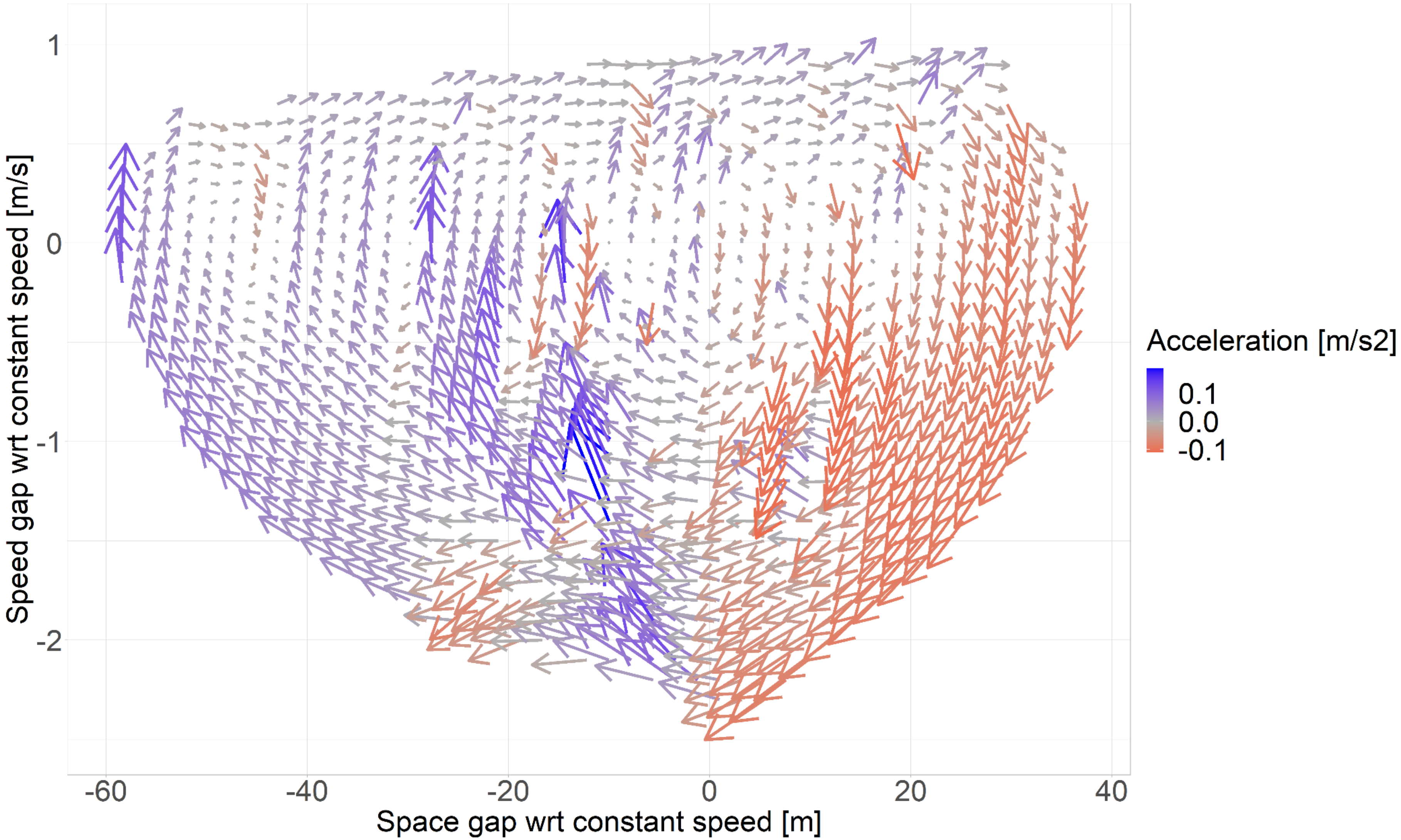
Leader-follower model

Follower is subject to speed variations

Yellow signals force the follower to decelerate



Analysis on recorded data from the Swiss network (50 trains)



Stochastic process models for 2 trains

We use stochastic processes of increasing complexity that model different situations

1. Speed follows an Ornstein-Uhlenbeck process **(OU)**

$$\textbf{[OU]:} \quad \begin{cases} \mathrm{d}v(t) = \beta(v_{\text{CRUISE}} - v(t))\mathrm{d}t + \sigma \mathrm{d}W(t) \\ \mathrm{d}s(t) = v(t)\mathrm{d}t \end{cases} \xrightarrow{\qquad\qquad} \text{Mean-reverts to } v_{\text{CRUISE}}$$

It can represent the process of a **human train driver** who knows the planned speed and continuously controls the train speed to be as close as possible

Stochastic process models for 2 trains

2. Doubly mean-reverting, doubly bounded process (**DMR**)

$$\textbf{[DMR]:} \quad \begin{cases} \mathrm{d}v(t) = \left[\beta(v_{\text{CRUISE}} - v(t)) + \alpha\left(v_{\text{CRUISE}}\, t - s(t)\right)\right]\mathrm{d}t + \widehat{\sigma}(v(t))\,\mathrm{d}W(t) \\ \mathrm{d}s(t) = v(t)\mathrm{d}t \end{cases}$$

where $\widehat{\sigma}(v) := \sigma\sqrt{\dfrac{v\cdot(v_{\text{MAX}} - v)}{v_{\text{CRUISE}}\cdot(v_{\text{MAX}} - v_{\text{CRUISE}})}}$

It can model how a **computer**, aware of precise position of current and ahead vehicle, can steer the system towards a desired space headway

- When a yellow signal is triggered, the train decelerates towards an approach speed
- **Full driving dynamics** combine a stochastic process with possible deceleration phases

Generalization to a string of trains

- Dynamics of follower *n* as a function of follower *n*-1

$$\textbf{[DMR]:}\quad \begin{cases} \mathrm{d}\boxed{v_n}(t) = \left[\beta_n(v_{\text{CRUISE}} - \boxed{v_n}(t)) + \alpha_n \left(\boxed{s_{n-1}(t) - s_n(t)}\right)\right] \mathrm{d}t + \widehat{\sigma}(v_n(t))\,\mathrm{d}W(t), \\ \mathrm{d}\boxed{s_n}(t) = v_n(t)\mathrm{d}t \end{cases}$$

- Compute energy consumption of each train and of the entire system

$$E_{s_1}^{s_2} = \int_{s_1}^{s_2} \max\{f(s), 0\}\, ds$$

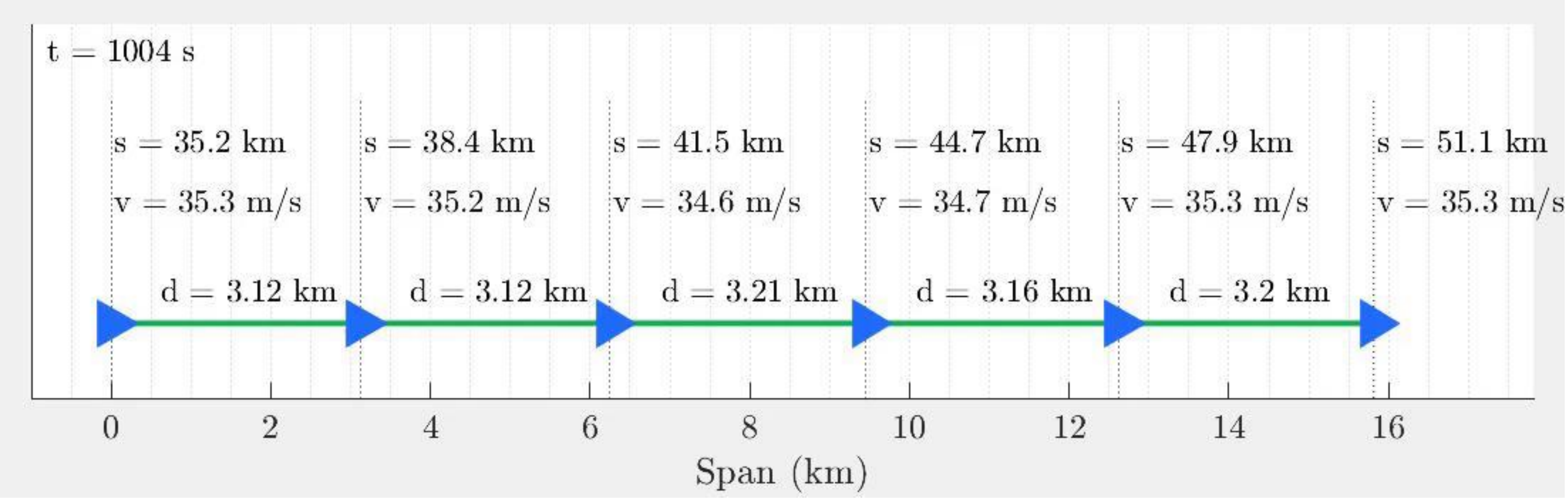
where the traction force fulfills

$$\begin{cases} \dfrac{dv(s)}{ds} = \dfrac{f(s) - R_{line}(s) - R_{train}(s)}{\rho \cdot m \cdot v(s)} \\ \dfrac{dt(s)}{ds} = \dfrac{1}{v(s)} \end{cases}$$

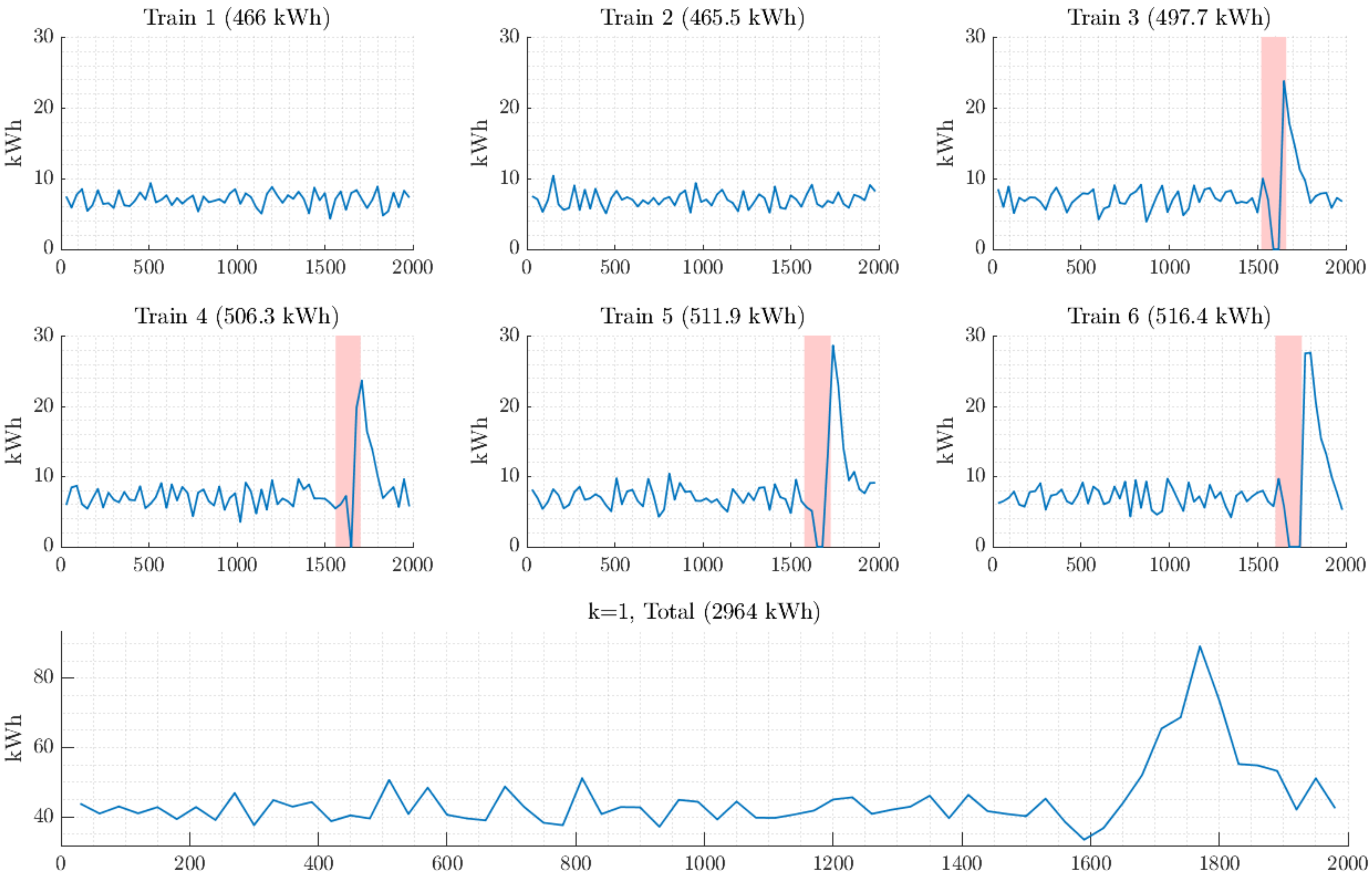
- We study the dynamics system using Monte Carlo simulation; hence, the above relations are discretized

Propagation of yellow signals

- Decelerating trains affect the follower in a cascade effect



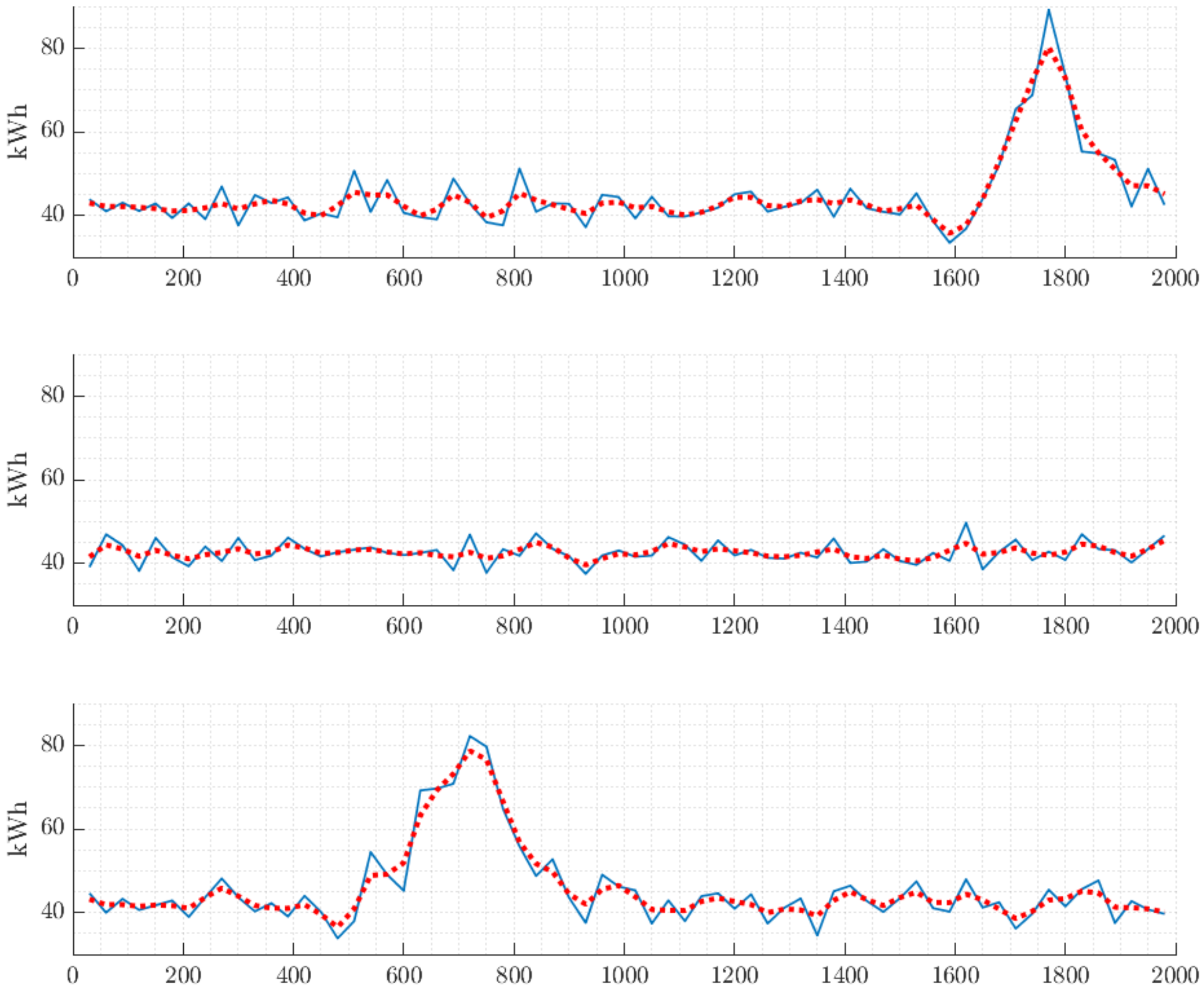
Energy consumption (1 trajectory)



Individual trains

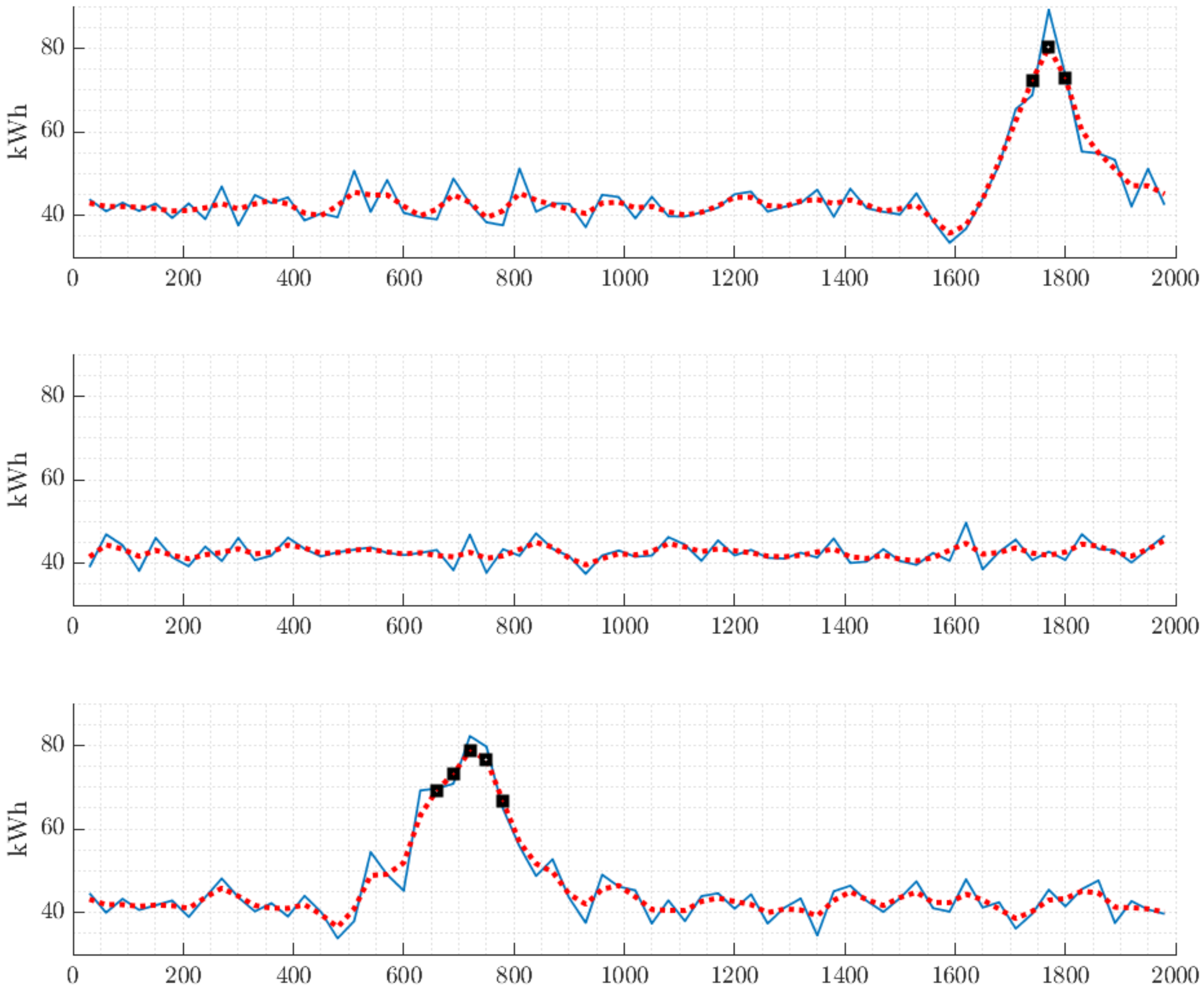
All trains

Peak detection



1. Exponential smoothing

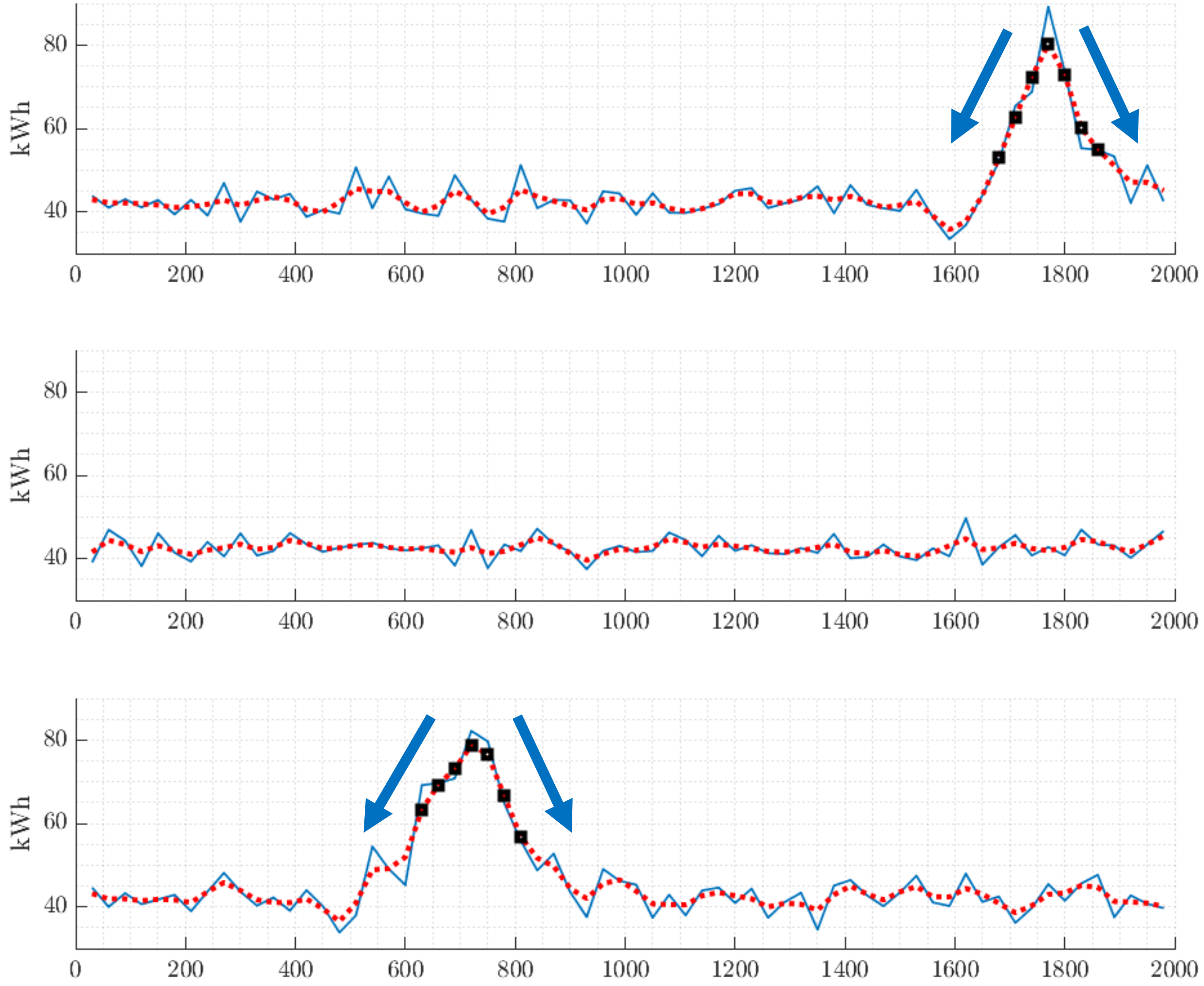
Peak detection



1. Exponential smoothing
2. Select points *t* such that

$$E_t \geq \alpha \cdot \mathrm{mean}(E) + \beta \cdot \mathrm{std}(E)$$

Peak detection



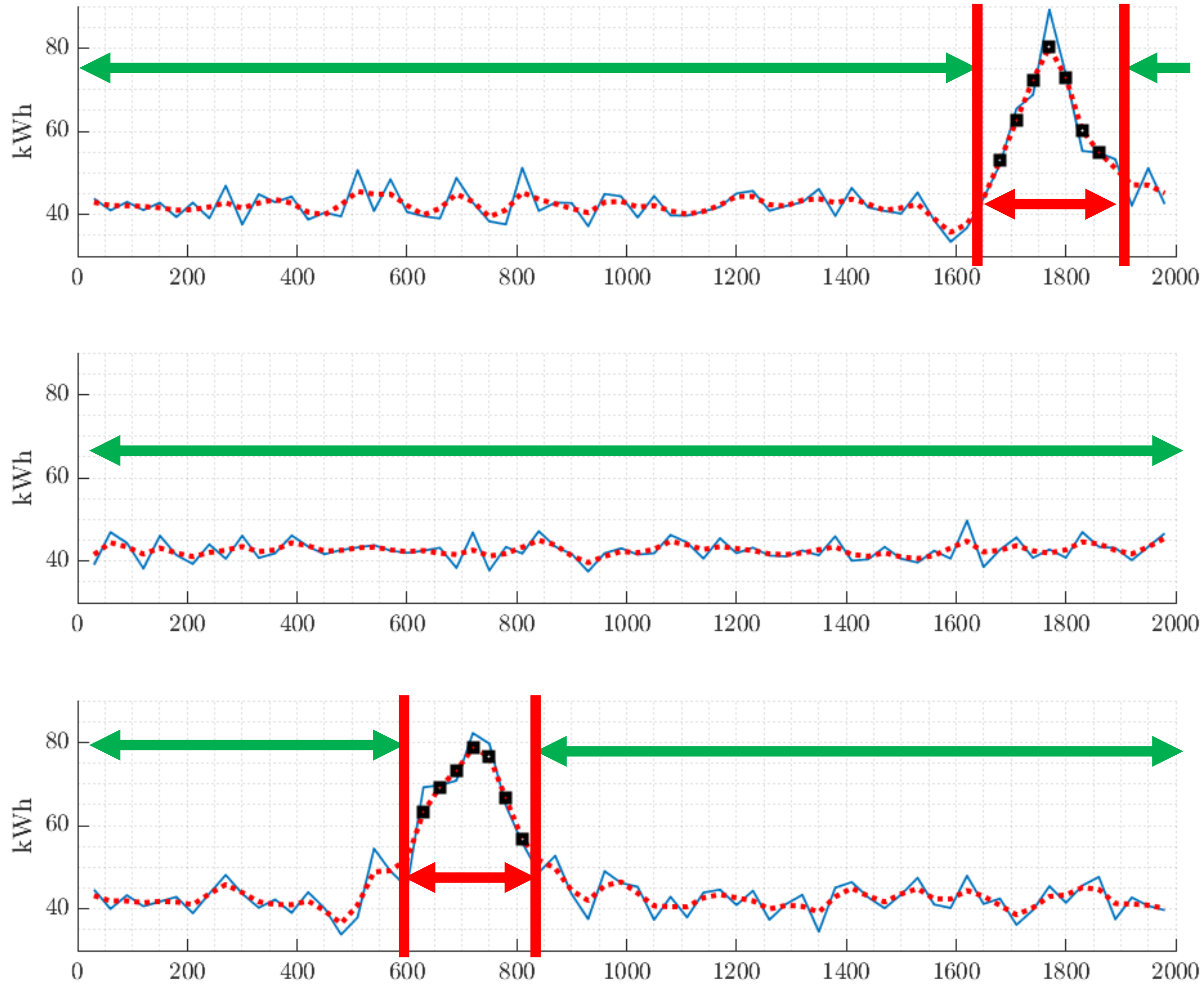
1. Exponential smoothing

2. Select points *t* such that

$$E_t \geq \alpha \cdot \text{mean}(E) + \beta \cdot \text{std}(E)$$

3. Reconstruct the peak

Peak detection

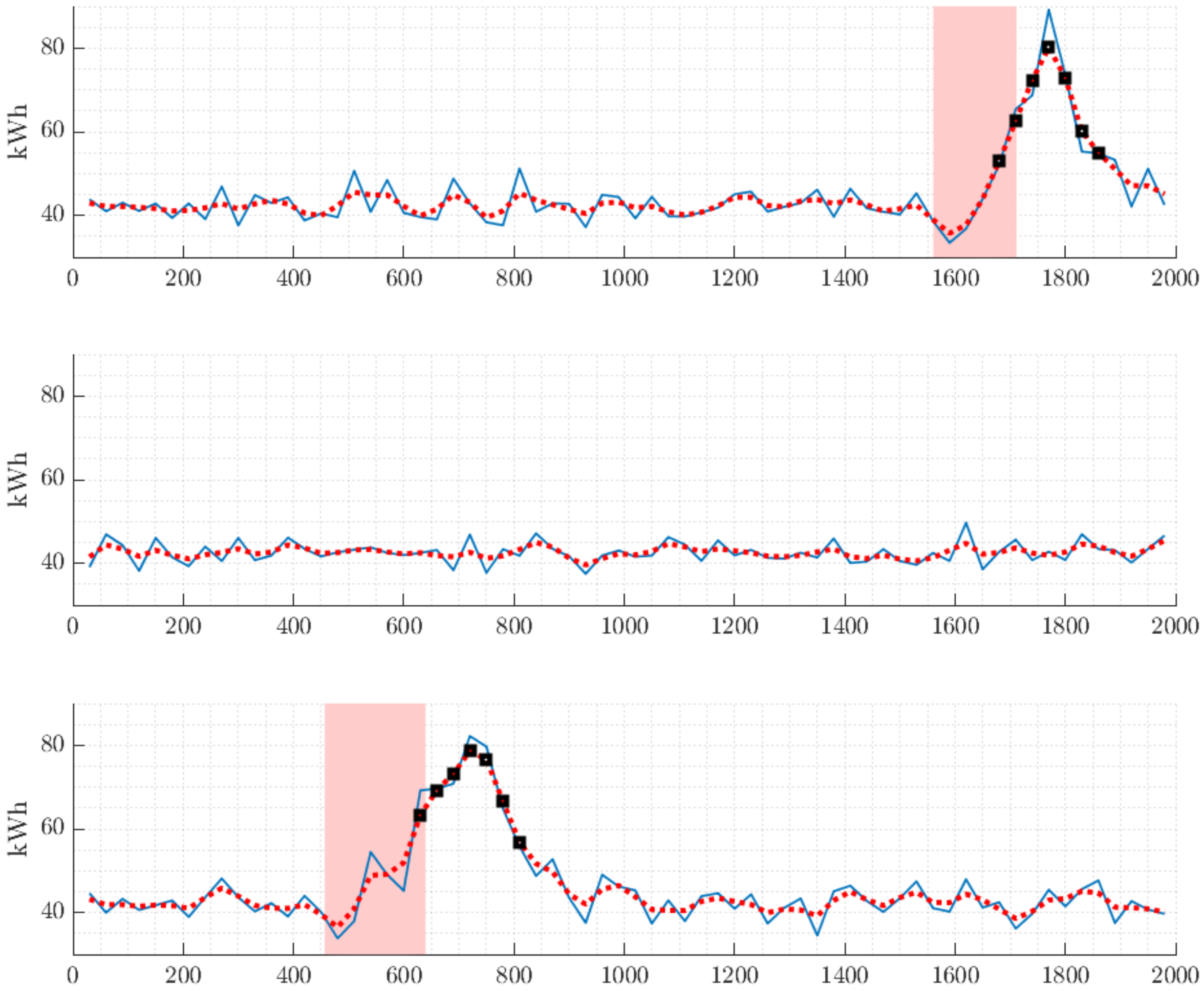


1. Exponential smoothing
2. Select points *t* such that

$$E_t \geq \alpha \cdot \mathrm{mean}(E) + \beta \cdot \mathrm{std}(E)$$

3. Reconstruct the peak
4. Separate peaks from non-peaks and examine the two regions

Peak detection



1. Exponential smoothing
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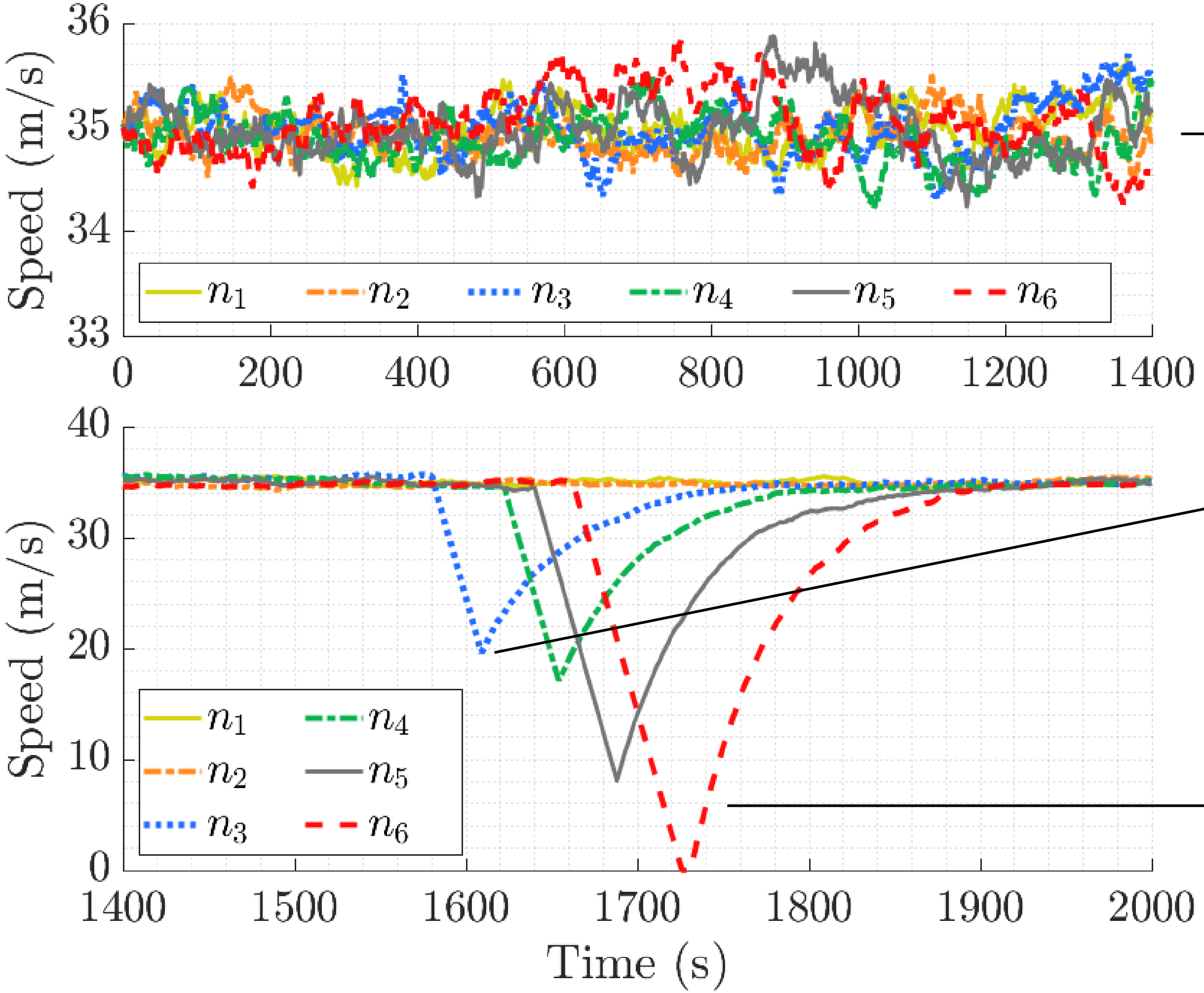
3. Reconstruct the peak
4. Separate peaks from non-peaks and examine the two regions

Peaks correspond to multiple trains accelerating after a yellow signal

Analysis of a trigger event (OU process)

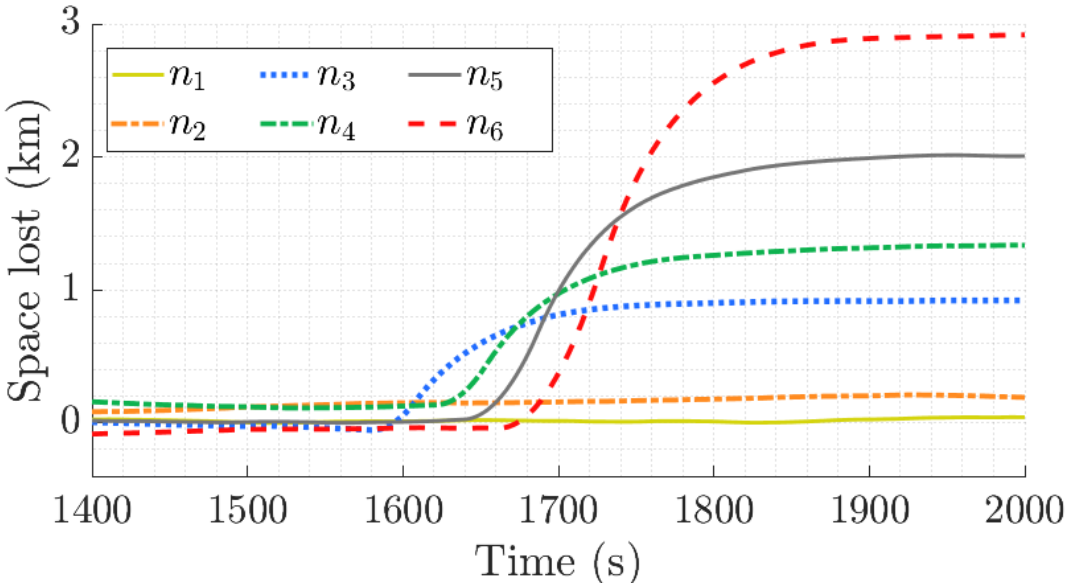


Speed fluctuations ±0.5 m/s for all trains due to stochastic process model (no yellow signal)

The third train triggers a yellow signal and decelerates until 20 m/s (approach speed given as input)

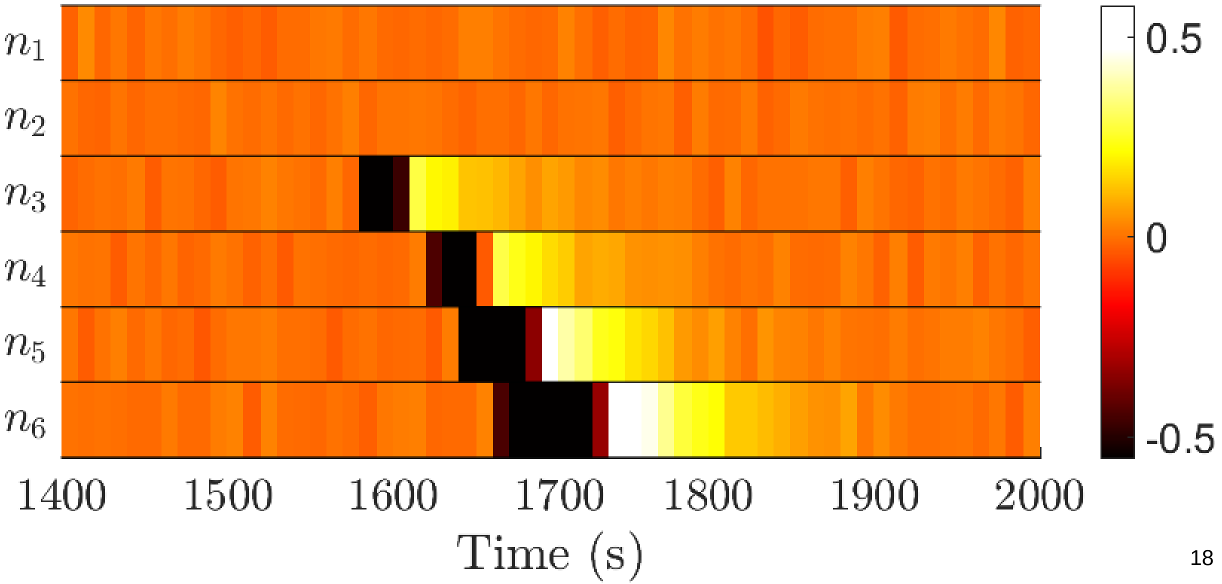
More downstream trains may have to decelerate more (or even stop) I order for the headway to be restored

Analysis of a trigger event (OU process)



- Space lost w.r.t. a fixed speed benchmark
- The space lost increases the more the train is downstream

- Small changes in acceleration due to stochastic process (shades of orange)
- Deceleration and acceleration phases are longer the more the train is downstream



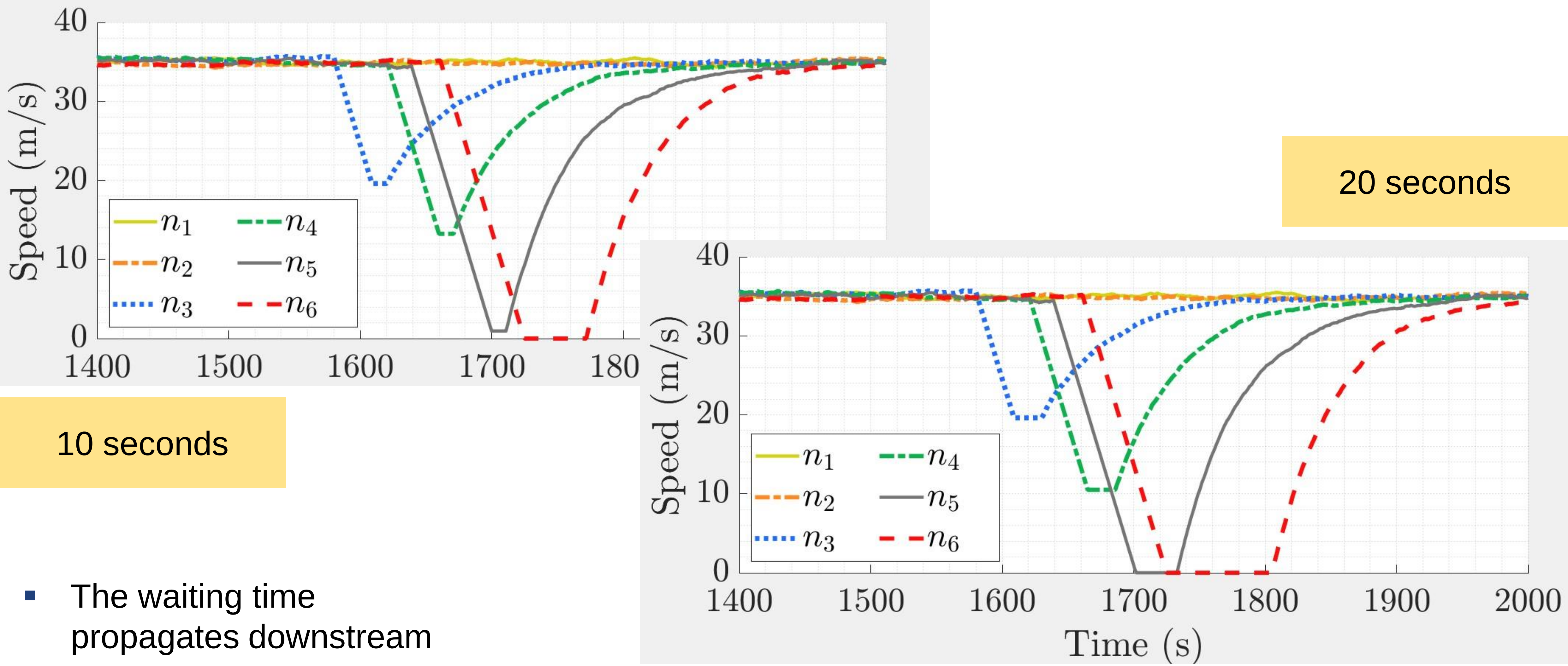
Average system performance

	Regularity	Energy
OU	Speeds (m/s) : 35 34.94 34.84 34.71 34.54 34.34 Space (km) : 35 35 34.9 34.8 34.7 34.6 Distance (km): 3.24 3.27 3.28 3.31 3.33 Triggers (%) : 0 12.4 29.4 42.6 52 57.2 FTTY (s) : 2000 1925 1807 1701 1627 1579	Mean out (kWh) : 42.52 Mean in (kWh): 63.02 Max (kWh) : 76.34 Extra (kWh) : 128.25 Total (kWh) : 2875.6
DMR	Speeds (m/s) : 35.01 35.01 35.01 35.01 35.01 35.01 Space (km) : 35 35 35 35 35 35 Distance (km): 3.2 3.2 3.2 3.2 3.2 Triggers (%) : 0 0 0 0.2 1.8 5.2 FTTY (s) : 2000 2000 2000 2000 1991 1965	Mean out (kWh) : 42.07 Mean in (kWh): 56.04 Max (kWh) : 63.88 Extra (kWh) : 54.38 Total (kWh) : 2821.5

Smoothing the peaks (work in progress)

	Impact on dynamics	Assumptions
Account for regenerative energy	**No** Just energy calculations	**Technology**
Maintain low speed for some time	**Yes** (fixed rules)	**No**
Implement control actions	**Yes** (optimization)	**Information** Power usage by other trains

Maintain low speed for a fixed time

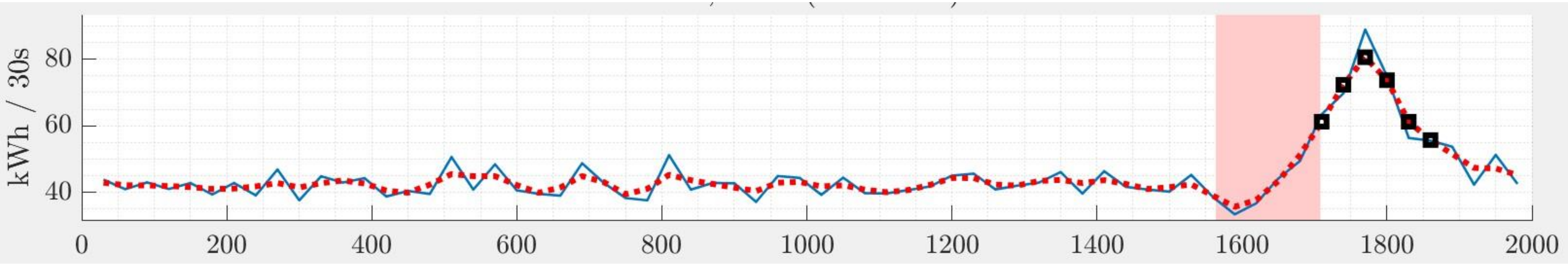


20 seconds

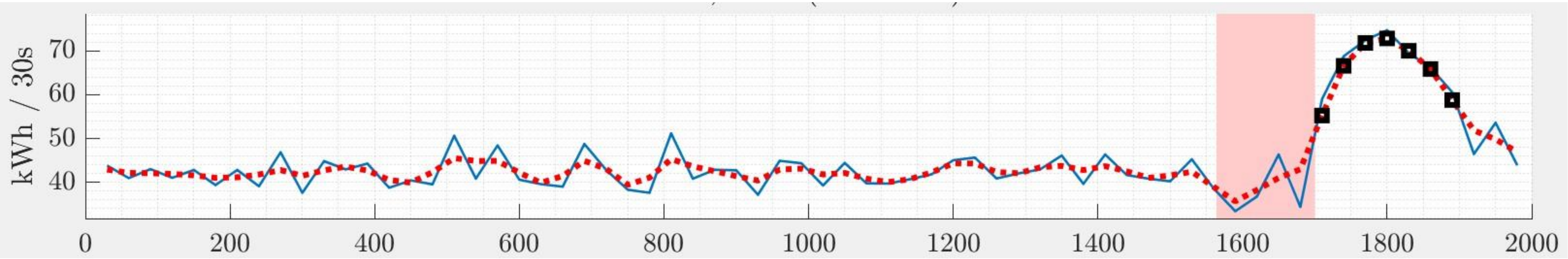
10 seconds

- The waiting time propagates downstream

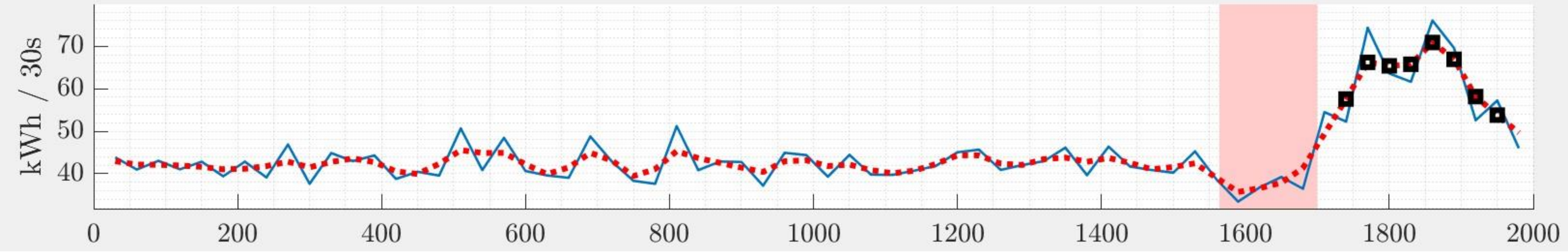
Maintain low speed for a fixed time



0 s



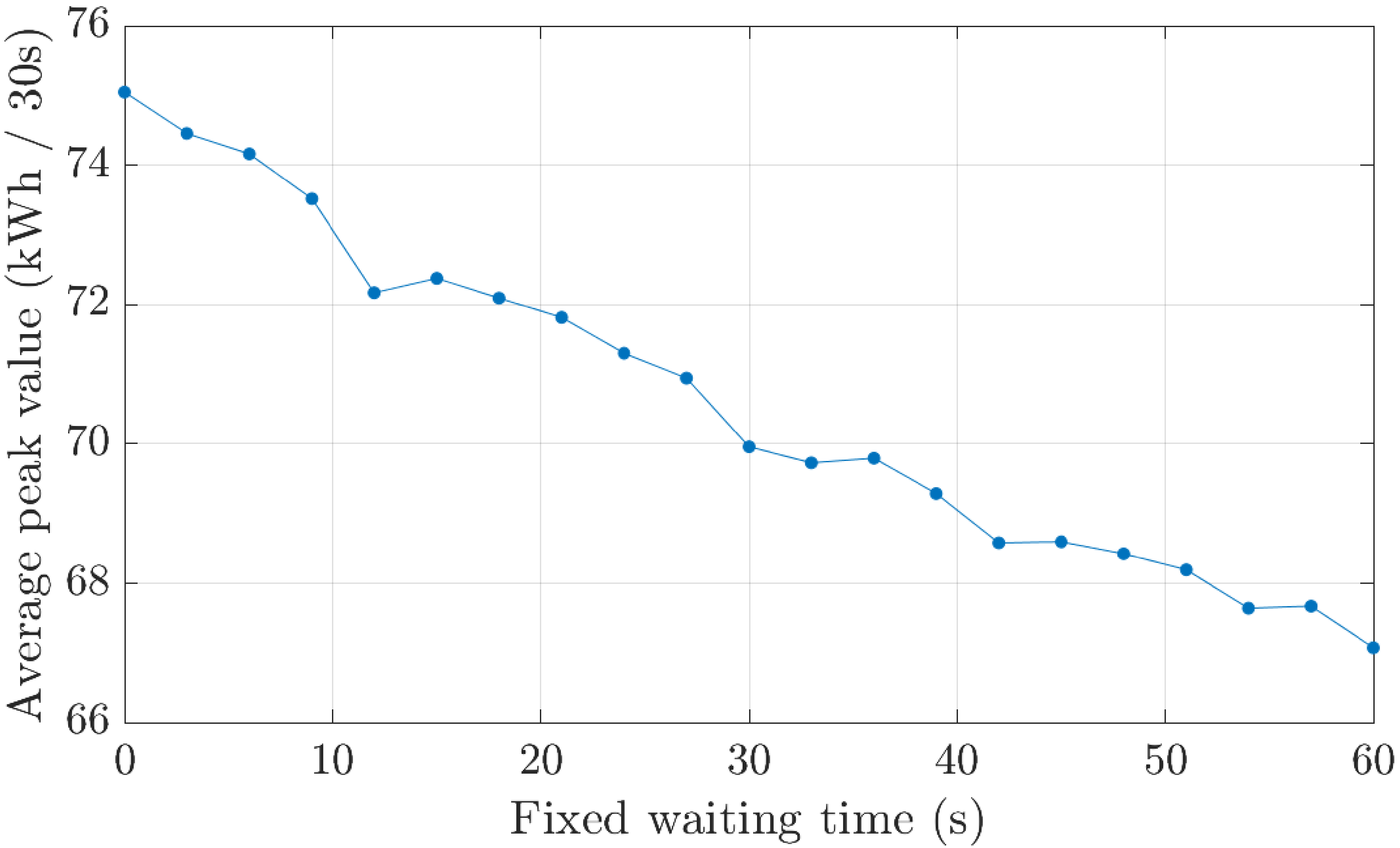
10 s



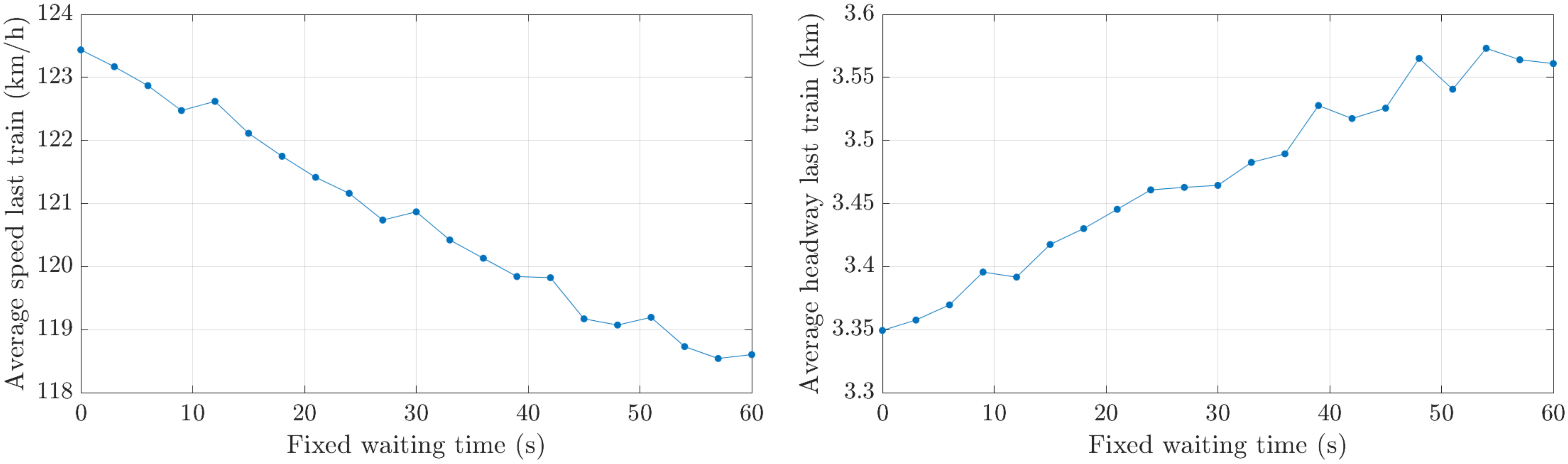
20 s

Maintain low speed for a fixed time

- What is the best value?
- The higher the waiting, the smaller the average peak
- The higher the waiting time, the smaller the average peak
- What are the implications for traffic regularity?

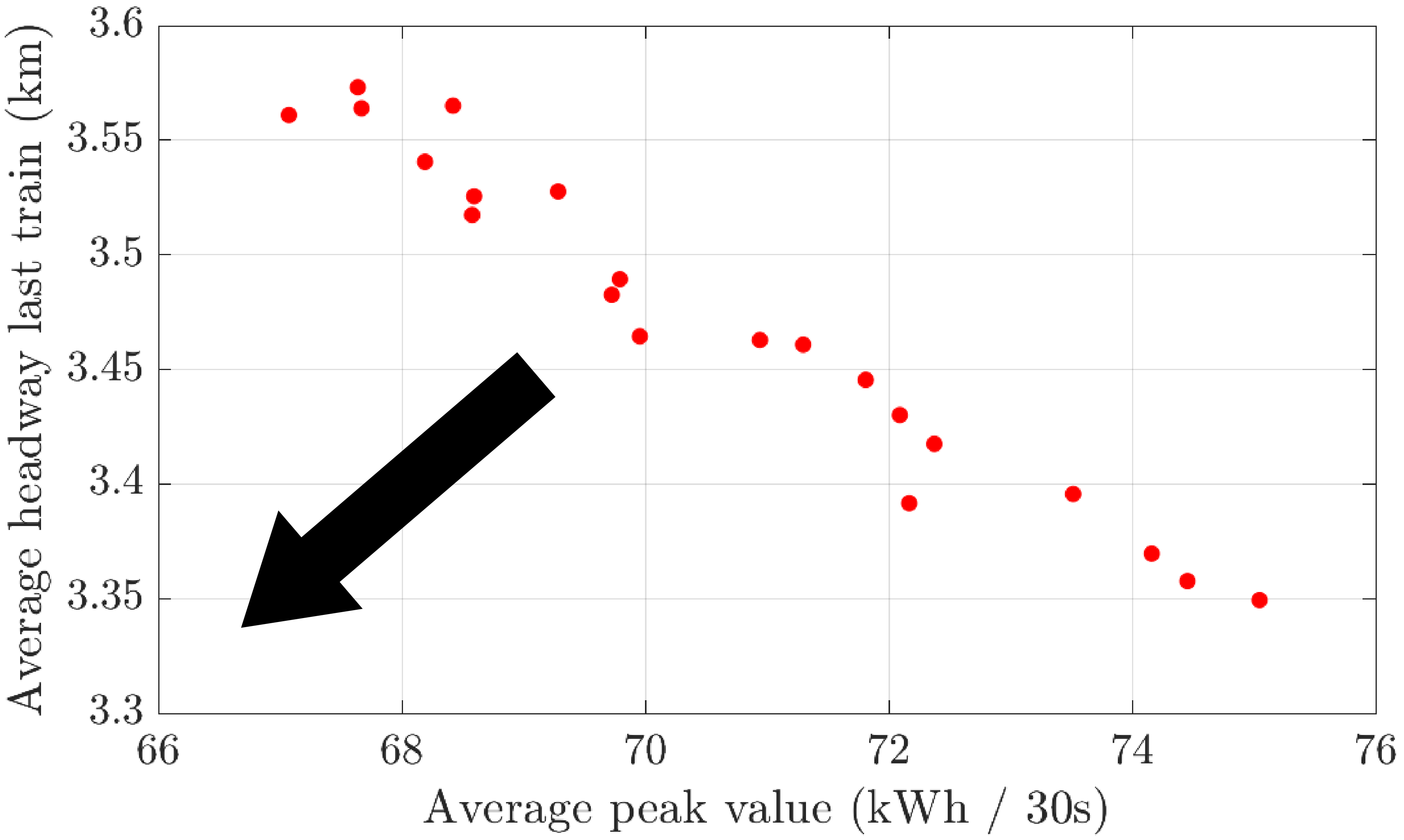


Maintain low speed for a fixed time



- Average train speed decreases and average headway increases (i.e., both worsen)
- This means that improving regularity and shaving the peaks are conflicting objectives

Maintain low speed for a fixed time



Summary of (preliminary) insights

- The model describing **ATO** is more efficient than that of a human driver in terms of both traffic regularity and energy consumption

- The considered strategies have the **potential to shave the peaks** considerably (we have tested so far only one of them)

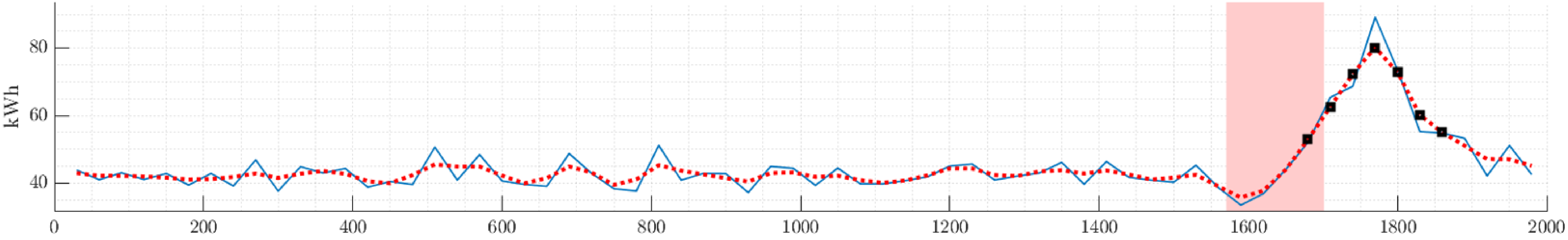
- There is a **trade-off** between traffic regularity (e.g., measured as average train speed) and energy performance (e.g., average height of peaks)

- Strategies to improve energy performance must be designed and tuned carefully to avoid significant losses in utilization capacity

Future work

- Complete implementation and comparison of peak shaving strategies
- Test the system under different conditions
- Calibrate stochastic process parameters to data (now chosen such that random speed variations are similar to what we observe)

Suggestions are welcome



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